Astroparticle Physics: The High Energy Tail of the Cosmic Ray Spectrum

Enrique Zas[a*]

[a]Departamento de Física de Partículas,
Universidade de Santiago de Compostela, E-15706 Santiago, Spain.
zas@fpaxp1.usc.es

In this article I review the main theoretical problems that are posed by the highest energy end of the observed cosmic ray spectrum, stressing the importance of establishing their composition in order to decide between proposed scenarios. I then discuss the possibilities that are opened by the detection of inclined showers with extensive air shower arrays. Recent progress in modelling magnetic deviations for these showers has allowed the analysis of inclined showers that were detected by the Haverah Park experiment. This analysis disfavours models that predict a large proportion of photons in the highest energy cosmic rays and open up new possibilities for future shower array detectors particularly those, like the Pierre Auger Observatory, using water Čerenkov detectors.

1. HIGH ENERGY COSMIC RAYS

Cosmic rays are elementary particles arriving at the Earth from outside that were discovered in the beginning of the 20th century as one of the main sources of natural radiation. The cosmic ray spectrum has been observed as a continuum at all energies since their discovery. Throughout this period cosmic rays have always been the source of the highest energy elementary particles known to mankind, and for this reason they have given birth to particle physics. The high energy tail of the spectrum as it is known today corresponds to energies up to 3 10^{20} eV and rates of a few particles per km^2 per century.

It is remarkable that the cosmic rays have a quite featureless power law energy spectrum which decreases as approximately the cube of the primary energy. For energies above the few hundred TeV the observed flux necessarily requires techniques that take advantage of the extensive air showers that the arriving particles develop as successive secondary particles cascade down into the atmosphere. Shower measurements allow the reconstruction of the arrival directions and the shower energy but the nature of the primary particle is extracted by a number of indirect methods.

For energies above few tens of GeV the detected particles, mainly protons, have arrival directions with a remarkably isotropic distribution. This is understood in terms of diffusive propagation in the galactic magnetic fields. As the energy rises above a given value that depends on the charge of the particle, propagation in the Galaxy should cease to be diffusive. Such high energy particles are expected to be extragalactic.

The observation of high energy cosmic rays has been recently reviewed by Nagano and Watson [1] who have shown that there is very good agreement between different experiments including the low and high energy regions of the spectrum. There is increasing evidence for a different component of the high energy end of the cosmic ray spectrum [2]. Combining data of five different experiments, AGASA, AKENO, Haverah Park, Stereo Fly's Eye and Yakutsk, Nagano and Watson conclude that there is a clear signal of a change of the spectral slope in the region just above 10^{18} eV [1]. Composition studies have also given indications that there is a change to light element composition for energies above $\sim 10^{18}$ eV [3] although this conclusion is model dependent

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to some extent [2]. Also the small anisotropy (4%) of 10^{18} eV cosmic rays in the direction of the galactic anticenter detected with AGASA disappears at higher energies [4].

The highest energy events detected present a serious challenge to theory and little is known about their origin. If they are protons they should attenuate in the Cosmic Microwave Background (CMB) over distances of order 50 Mpc. Such attenuation was predicted to appear in the cosmic ray spectrum as a cutoff, the Greisen-Zatsepin-Kuz'min (GZK) cutoff, just above 4 10^{10} GeV [5]. If they are photons or iron nuclei it turns out that interactions with the radio and the infrared backgrounds are respectively responsible for attenuations over similar or even shorter distances. No such features are seen in the observed cosmic ray spectrum. If they are produced sufficiently close to us to avoid the cutoff then the arriving particles should be pointing to their sources. This seems difficult to accommodate because there are very few known astrophysical sources capable of reaching the observed energies and on the other hand there is little evidence for the anisotropy that would result.

This article firstly discuses the problem presented by the high energy end of the cosmic ray spectrum with emphasis in the role of composition. Then it outlines new progress made in understanding different features of inclined showers illustrating how these showers can contribute to the composition issue reviewing the results obtained by a recent analysis of the inclined data in Haverah Park.

2. ORIGIN: AN UNSETTLED ISSUE

The discovery of events with energies above 10^{20} eV (100 EeV) dates back to the 1960's, to the early days of air shower detection experiments [6]. Since then they have been slowly but steadily detected by different experiments as illustrated in Fig. 1. Now there is little doubt about the non observation of a GZK cutoff, with over 17 published events above 10^{20} eV and five preliminary new events from HiRes [7]. On the contrary the data suggests that the spectrum continues smoothly within the statistical errors, possibly with a change of slope. On the other hand the data show no firm evidence of anisotropy but the significance of such studies is even more limited by the poor statistics.

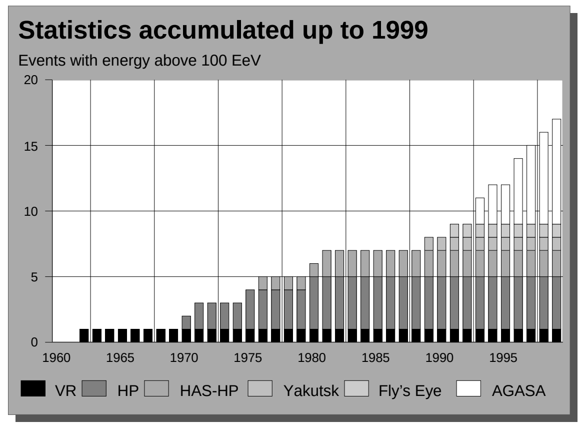

Figure 1. Accumulated events of energy exceeding 10^{20} eV plotted as a function of time as detected by different experiments: Volcano Ranch (VR), Haverah Park (HP), Horizontal Air Showers in Haverah Park (HAS-HP), Yakutsk, Fly's Eye and AGASA.

Both the details of the spectrum at the cutoff region and the extent to which the arrival directions of these particles cluster in the direction of their sources are very dependent on a number of unestablished issues. These include the source distribution, the distance of the nearest sources, their emission spectra, the intervening magnetic fields and of course on the nature of the the cosmic rays themselves or composition. If these particles are nuclei or photons the observational evidence is suggesting that these are coming from relatively nearby sources compared to the 50 Mpc scale. The conclusive power of observations is however strongly limited by both the poor statistics and a complex interrelation of hypotheses, but the situation is bound to change in the immediate future with a new generation of large aperture experiments, some like HiRes [7]

already in operation, others in construction [8] and many others in planning [9,10]. The complex puzzle that connects particle physics, magnetic fields, and cosmic rays has attracted the attention of many fields in physics.

In a conventional approach these particles would be nuclei as the bulk of the cosmic ray spectrum which are accelerated through stochastic acceleration as suggested by Fermi in 1949. This happens every time charged particles cross interfaces between regions that have astrophysical plasmas with different bulk motions, such as shock fronts. Transport is assumed to be diffusive in the plasma's magnetic field and on average in these processes a very small fraction of the bulk plasma kinetic energy is transferred as a boost to the individual particles, that typically end up with a power like spectrum. Acceleration of a particle of charge Ze to an energy E is strictly limited by dimensional arguments to objects that are sufficiently large or have sufficiently large magnetic fields. Basically for a particle with momentum p to be able to undergo such a boost, propagation must be diffusive, or equivalently the accelerator region L must be larger than the Larmor radius of the particle, R, in its characteristic magnetic field B:

$$R = \frac{p}{ZeB} < L \qquad E \simeq pc < ZeBcL \tag{1}$$

The requirement is well known by accelerator designers and is the ultimate reason for their high cost. It turns out that few of the known astrophysical objects satisfy the minimum requirements to accelerate particles to 10^{20} eV. This is conveniently illustrated in a plot first conceived by Michael Hillas [11] which is reproduced in Fig. 2. A number of possible scenarios are being discussed; they imply acceleration in some objects including young pulsars, Gamma Ray Bursts (GRB), our own galaxy, active galaxies and the local group of galaxies [12]. The power supply needed to keep the observed cosmic rays at the highest energies is consistent with the known power and distributions of these objects [2].

It is difficult to explain the observed flux spectrum in this conventional approach. A solution in which particles are accelerated nearby has difficulties because there are very few objects which

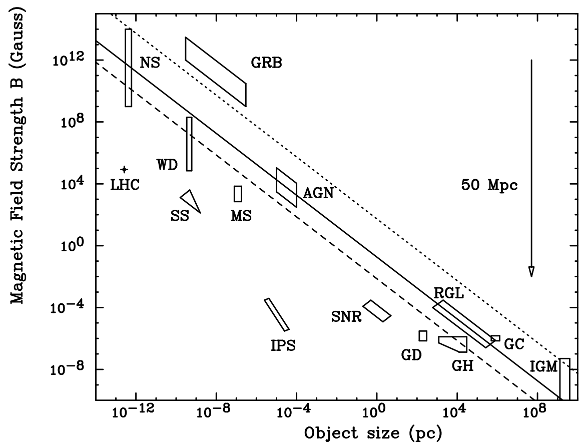

Figure 2. Hillas Plot of the typical size of a possible accelerator L versus its magnetic field strength B. From upper left to lower right the astrophysical objects correspond to Neutron Stars, White Dwarfs, Sun Spots, Magnetic Stars, Gamma Ray Bursts, Active Galactic Nuclei, Inter Planetary Space, Supernovae Remnants, Radiogalaxy Lobes, Galactic Disk, Galactic Halo, Clusters of Galaxies and the Inter Galactic Medium. Also shown is the point corresponding to the largest accelerator in planning LHC. The straight lines represent the limits given by Eq (13) for protons (full), Iron nuclei (dashed) and for protons assuming a 10% efficiency (dots).

are capable of accelerating particles to the maximum observed energies. Moreover many such objects are either too large or too distant for the cosmic ray spectrum detected at the Earth not to show the predicted GZK cutoff. If the sources were to be galactic no absorption cutoff would be expected but some spectral features are predicted for primary protons that are produced at a distance of more than a few Mpc. On the other hand the non observation of anisotropy complicates the puzzle, because the location of the possible accelerators in our vicinity is pretty well known. Primary protons having energies in the 10^{20} eV range are expected to be little deviated in the galactic magnetic fields. Our knowledge of extragalactic

magnetic fields is poor but bounds on extragalactic magnetic fields also imply that the deviations of protons produced in the few Mpc range are not large. There are however possible configurations of the extragalactic magnetic fields that could explain many of the ultrahigh energy events as coming from a single source [13]. The issue is far from being resolved and knowledge about composition is bound to play a crucial role for future progress in understanding.

Motivated by particle physics beyond the standard model, many alternatives have been proposed that avoid acceleration and others that postulate different particles or different interactions. These include annihilation of topological defects created in the early universe, heavy relics that survive from the primeval bath, non thermal particles that couple to gravity, or wimpzillas and annihilation of relic neutrinos with messenger neutrinos coming from remote places [12]. As regards composition two large categories of possible scenarios can be made namely those in which the observed particles are accelerated and those in which they are decay products of other particles. These two classes differ greatly in composition. A knowledge of composition is doubly important because firstly it may decide between these two classes of solutions and secondly because it would simplify the task of interpreting anisotropy measurements.

3. COMPOSITION

The models that depend on acceleration can reach higher energies if the accelerated particles have large charge Z. This shows as a different restriction line in Fig 2. The relative composition of different nuclei resulting from such a scenario will depend on the local abundances of the different nuclei and on the energy. Depending on distance to the source and the surrounding environment there may be energy losses, absorption and the production of secondary particle fluxes. For instance in Active Galactic Nuclei (AGN) models the accelerated protons are expected to interact with ambient light or matter to produce pions that decay into photons and neutrinos. The neutrinos can reach the Earth unattenuated and provide a signature of proton acceleration. Unless the environment becomes opaque to protons the relative fluxes of neutrinos and protons that reach the Earth should be a number of order one or smaller, just because neutrinos are secondaries with repect to protons. The relative fluxes of photons and protons would be similar to neutrinos or smaller depending on the photon absorption both at the source and during transport to Earth. Ratios of the same order of magnitude would apply to most acceleration models.

Most of the non accelerating alternatives postulate the cosmic rays are products of the decay of other more massive particles produced by different mechanisms. Typically these particles of mass of 10^{24-25} eV (often an X particle) decay into standard model particles which eventually fragment into hadrons, mostly pions and a small fraction of order 3% of nucleons. While neutral pions decay into photons charged pions decay into neutrinos. Fragmentation processes, known form accelerator experiments and extrapolated to the high energies, become the common reference point for these mechanisms. For this reason all these models share a very similar composition dominated by photons and neutrinos which typically are about ten times more numerous than nucleons at the production site.

Depending on the source distribution the relative fluxes of these particles are modified through their interactions with the background radiation fields. The neutrinos are the particles that preserve their production spectrum without being attenuated. Protons get attenuated in few tens of Mpc in the cosmic microwave background, (the GZK cutoff), while photons are attenuated already in few Mps mainly through pair production in the radio background. As a result the ratio of neutrinos to protons can in principle become higher at the Earth than when they are produced if the sources are quite distant or cosmologically distributed. Many of the proposed mechanisms are expected to cluster in our galactic halo. This possibility is receiving a lot of attention because it would provide a relatively natural explanation for the absence of the GZK cutoff. In that case however the sources will be quite near and the ratio of photons to nucleons should be expected to be of

order 10, close to its value at production. Other sources are not expected to cluster and hence the photon to nucleon ratio is expected to drop to values close to one. The ratio of photons to nucleons depends on the source distribution and is rather sensitive to clustering.

4. INCLINED SHOWER FEATURES

Most air shower detectors in existence consist on arrays of particle detectors that sample the extensive air shower front as it reaches the ground. Multiple particle production takes place in the successive high energy interactions produced as the shower penetrates the medium. As a result the number of particles in the shower front increases exponentially. When the average particle energy in the front becomes too low for multiple particle production the shower reaches it maximum number of particles. The development of these showers is typically governed by the radiation length in the material which is of order 36 g cm^{-2} in air and shower maximum, which is only logarithmically dependent on the primary particle energy, occurs at a couple of thousand meters for vertical showers of energies of order 10^{20} eV.

Vertical showers are close to shower maximum when reaching the Earth's surface, have pretty good circular symmetry and are less affected by the Earth's magnetic field. It is thus not surprising that air showers have traditionally been studied at close to vertical incidence, typically for zenith angles below $45°$, in summary because it is much simpler. Moreover in most extensive air shower arrays the particle detectors are oriented to have maximum collection area for vertical incidence. Since these detectors are often scintillator sheets, they tend to become very inefficient for very inclined showers.

As the zenith angle increases the traversed atmospheric depth rises from 1000 to close to 36000 g cm^{-2}. As a result the shower maximum is reached in the upper layers of the atmosphere and most of the shower is absorbed before reaching the ground. It has been known for a long time that weakly interacting particles such as neutrinos can induce close to horizontal air showers deep in the atmosphere with particle distributions that are quite similar to vertical showers [14,15]. Air shower array detectors looking in the close to horizontal direction can thus be sensitive to high energy neutrino fluxes [16]. In fact most bounds on neutrino fluxes have already been obtained from air shower experiments [17,18].

The original motivation of studying inclined showers was to understand the cosmic ray background to the neutrino induced showers. Although the electromagnetic part of the air shower induced by an inclined cosmic ray is indeed absorbed before reaching ground level, the shower front however also contains muons which are mainly produced by charge pion decay when the primary particle is a hadron. These muons do travel practically unattenuated all the slant atmospheric depth and produce density patterns on the ground that are much affected by the Earth's magnetic field. It has recently become quite clear that such inclined showers can be analysed. This not only nearly doubles the aperture of any air shower array but, when combined with vertical measurements, it has a remarkable potential for the study of primary composition [19].

Much development in this field has been possible by the modelling of the muon density patterns produced by inclined showers under the influence of the Earth's magnetic field [20]. The lateral distributions of muons in inclined showers can be understood in terms of a simple model [21] in which the magnetic field is firstly neglected. The model stresses two important facts that have been extensively checked with simulations in the absence of a magnetic field [21]: Most of the muons in an inclined shower are produced in a well defined region of shower development which is quite distant from the ground and the lateral deviation of a muon is inversely correlated with its energy.

Indeed most of the fundamental properties of these inclined showers are governed by the distance and depth travelled by the muons. It is remarkable that the average slant distance travelled by the muons is of order 4 km for vertical showers, becomes 16 km at $60°$ and continues to rise as the zenith angle rises to reach 300 km for a completely horizontal shower. This distance plays a crucial role as a low energy smooth cutoff for

the muon energy distribution. For inclined showers the muons must have much more energy at production to reach ground level without decaying than in the vertical case. Both the travel time and the muon energy loss become relevant.

The model simply assumes that all muons are produced at a given altitude d with a fixed transverse momentum $p_\perp$ that is uniquely responsible for the muon deviation from shower axis. In the transverse plane to the shower at ground level the muon deviation, $\bar{r}$, is inversely related to muon momentum p. The density pattern has full circular symmetry when there is no magnetic field. When the magnetic field effects are considered the muons deviate a further distance δx in the perpendicular direction to the magnetic field projected onto the transverse plane $\vec{B}_\perp$, given by:

$$\delta x = \frac{e|B_\perp|d^2}{2p} = \frac{0.15|B_\perp|d}{p_\perp}\,\bar{r} = \alpha\,\bar{r}, \qquad (2)$$

where in the last equation $B_\perp$ is to be expressed in Tesla, d in m and $p_\perp$ in GeV. As the muon deviations are small compared to d they can be added as vectors in the transverse plane and the muon density pattern is a relatively simple transform of the circularly symmetry pattern. The muon patterns in the transverse plane can be projected onto the ground plane to compare with data as well as standard simulation programs.

Eq. 2 is telling us that all positive (negative) muons that in the absence of a magnetic field would fall in a circle of radius $\bar{r}$ around shower axis, are translated a distance δx to the right (left) of the $\vec{B}_\perp$ direction. The dimensionless parameter α measures the relative effect of the translation. For small zenith angles d is relatively small and $\alpha << 1$ so that the magnetic effects are also small, and results into slight elliptical shape of the isodensity curves.

For high zeniths however $\alpha > 1$ the magnetic translation exceeds the deviation the muons have due to their $p_\perp$. In this case *shadow* regions with no muons are expected in the muon density profiles. For an approximate $p_\perp \sim 200$ MeV and $B_\perp = 40$ μT this happens when d exceeds a distance of order 30 km, that is for zeniths above $\sim 70°$. These shadow regions in the transverse plane are indeed an outstanding feature of the ground density profiles at high zeniths as seen in the simulations.

Model	A	β	N_μ (10^{19} eV)
SIBYLL	1	0.880	3.3 10^6
	56	0.873	5.3 10^6
QGSJET	1	0.924	5.2 10^6
	56	0.906	7.1 10^6

Table 1
Relationship between muon number and primary energy for proton and irons in two hadronic models (see equation 3).

The simple model can be actually generalized to account for muon energy distributions as a function of distance to shower axis, and improved using the correlation between the average muon energy and the distance to shower axis as obtained in dedicated simulations. When all this is done the obtained muon density patterns are shown to be accurately reflect those obtained with simulations and this proves to be a very useful tool for the study of inclined showers.

For each zenith angle the primary particle energy sets the normalization of the particle densities. For proton primaries the total number of muons in the shower scales with the proton energy E as:

$$N = N_{ref}\ E^{\beta} \qquad (3)$$

where β is a constant. It is remarkable that the shape of the lateral distribution of the muons does not significantly change for showers of energy spanning over three orders of magnitude. The same happens for heavier nuclei with slightly different parameters. The results are slightly model dependent. Two alternative hadronic interaction models have been compared, the Quark Gluon String Model (QGSM) and SIBYLL to give also the same behaviour with also different parameters. Table 1 illustrates these effects.

As a final result the muon distributions can be represented by continuous functions which are analytically obtained once we know the main features of a shower in the absence of magnetic field.

In practice this implies that only different zenith angles have to be simulated. Different azimuths are obtained by adequate transformations of the showers without magnetic deflections. The algorithm is fast and allows detector simulation and also event by event reconstruction of data obtained by air shower experiments.

5. PHOTON COMPOSITION

This powerful technique has been used to analyse the inclined shower data obtained in the Haverah Park array. The Haverah Park detector was a 12 km^2 air shower array using 1.2 m deep water Čerenkov tanks that was running from 1974 until 1987 in Northern England which has been described elsewhere [22]. It is possibly the most appropriate detector for this study because the water Čerenkov tanks have a uniquely large cross section to sample shower fronts of horizontal air showers. Moreover the Čerenkov technique gives larger signals for muons than for electrons simply because the muons have typically larger energies and travel through the whole detector.

A careful study has been made of the energy deposition of signal in water Čerenkov tanks by horizontal muons using conventional simulation programs for this purpose [23]. A number of effects have to be considered to interpret the observed data. Inclined particles can produce light that falls directly into the phototubes without being reflected in the tank walls. Horizontal muons produce more signal through delta rays because on average they have higher energies than in vertical showers. There is a significant signal deposited by electromagnetic particles that arise mainly through muon decay. Finally the higher energy muons are more likely to deposit more energy in the tanks because of catastrophic energy losses. The event rate as a function of zenith angle has been simulated with careful treatment of all these effects using the muon distributions obtained as described in the previous section. The qualitative behaviour of the registered rate is well described in the simulation and the normalization is also shown to agree with data to better than 30% using the measured cosmic ray spectrum for vertical incidence, assuming proton primaries and

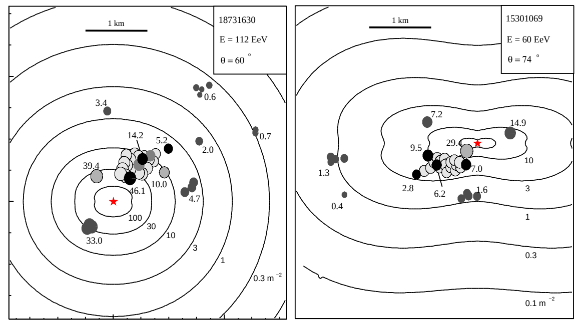

Figure 3. Density maps of two events in the plane perpendicular to the shower axis. Recorded muon densities are shown as circles with radius proportional to the logarithm of the density. The detector areas are indicated by shading; the area increases from white to black as 1, 2.3, 9, 13, 34 m^2. The position of the best-fit core is indicated by a star. Selected densities are also marked. The y-axis is aligned with the component of the magnetic field perpendicular to the shower axis.

using the QGSM model [20].

More impressive are the results of fits of the models for muon densities to the observed particle densities sampled by the different detectors on an event by event basis. The nearly 10,000 events recorded with zenith angles above 60° have been analysed for arrival directions, impact point and primary energy in the assumption the primaries are protons. A complex sequence of arrival direction and density fits is performed to minimize the effect of correlations between energy and arrival directions.

The analysed date is subject to a set of quality cuts: the shower is contained in the detector (distance to core less than 2 km), the χ^2 probability of the event is greater than 1% and the downward error in the reconstructed energy is less than 50%. These cuts ensure that the events are correctly reconstructed and exclude all events detected above 80°. Examples of reconstructed events compared to predictions are illustrated in Fig. 3. Two new events with energy exceeding 10^{20} eV have been

revealed. The results have been compared to a simulation that reproduces the same fitting procedure and cuts using the cosmic ray spectrum deduced from vertical air shower measurements in reference [1]. The agreement between the integral rate above 10^{19} eV measured and that obtained with simulation is striking when the QGSJET model is used. Sibyll leads to a slight underestimate [19].

The universality of the muon lateral distribution function is very powerful and once the equivalent proton energy is determined for all events, the corresponding energies in the assumption that the primaries are iron nuclei (photons) can be obtained multiplying the proton energy by a factor which is ~ 0.7 (6) for 10^{19} eV. As a result when a photon primary spectrum is assumed the simulated rate seriously underestimates the observed data by a factor between 10 and 20. A fairly robust bound on the photon composition at ultra high energies can be established assuming a two component proton photon scenario. The photon component of the integral spectrum above 10^{19} eV ($4\ 10^{19}$ eV) must be less than 41% (65%) at the 95% confidence level. Details of the analysis are presented in [19].

The results of this method when applied to a first analysis of inclined showers produced by cosmic rays above 10^{19} eV demonstrates that the study of inclined showers not only can double the acceptance of air shower arrays but it can be a very useful tool for the study of photon composition.

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